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MEASUREMENTS OF SHUTTLE GLOW ON MISSION STS 41-G

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ABSTRACT

The analysis of data from a set of experiments conducted during Mission STS 41-G by the National Research Council and the Air Force Geophysics Laboratory has shown that the intensity of the shuttle glow measured during this mission was more than an order of magnitude less than the intensity measured under similar conditions on earlier flights. In addition the thruster-enhanced glow was found to be spectrally continuous at the 0.4 nm resolution of the optical systems. Two separate activities, namely the Canadian Orbiter Glow (OGLOW) experiment and the USAF Auroral Photography Experiment (APE), were conducted simultaneously during STS 41-G and resulted in similar findings. The goals of both the OGLOW and the APE were to image earth aurora and airglow as well as glows emanating off shuttle surfaces. The experimental apparatus used for each experiment was a separate, hand-held, image intensified camera system with appropriate front-end optics. The interferometry data reported here were obtained using Fabry-Perot techniques.

INTRODUCTION

The analysis of photographic data obtained as part of the STS-3 Pathfinder Mission in March of 1982 revealed the presence of a spatially diffuse glow emanating from ram-facing shuttle surfaces exposed to atmospheric gases (Banks et al., 1983). These authors reported that the shuttle glow emissions were apparently from the gas phase near the surface rather than being a pure surface glow or reflection. Although this radiant emission was for the most part unanticipated it was strongly reminiscent of earlier Atmospheric Explorer (AE) satellite data (Torr et al., 1977) pertaining to an anomalous light source measured while the satellite was at low altitudes. The speculation at the time of the satellite observation was that the source of this anomalous light was an interaction of atmospheric gases and the satellite although continued interest in the subject was less than widespread (Yee and Abreu, 1982). The celebrated nature of the shuttle glow phenomena kindled a renewed, and more widespread, interest in the source of the emission as evidenced by numerous theoretical claims and experiments which have followed the initial shuttle observations.

The physical characteristics of the shuttle glow can be described in terms of the somewhat overlapping categories of the glow intensity, its spatial extent, and its spectral content. We consider here each of these topics and compare the shuttle glow measurements to satellite observations. It is noted, however, that the comparison is not straightforward due to

88 10 ~ 328

differences in the orbital characteristics, the local environment, and the instrument viewing geometries for each vehicle. For example, an anomalous radiant source measured within the narrow bandpass of an outward-looking instrument aboard an elliptically-orbiting, long duration, spinning satellite is not easily compared to a glow which appears to radiate off shuttle tail sections and which can be seen from the crew compartment. It is reasonable to assume, however, that mechanisms which produce glows on shuttle might also operate within a satellite environment although existing data sets suggest that the dominant source mechanisms in each case are different (Green, 1985; Yee et al, 1985).

The shuttle glow intensity has been observed to be a function of altitude, vehicle attitude, and surface temperature. Typically, these glow measurements are edge-on measurements of the shuttle's tail section as seen from the aft flight deck; that is, the crew compartment just forward of the payload bay. This viewing geometry provides a significant path for measured emissions just above the tail section. Mende et al. (1984b) have shown quite convincingly that the intensity of the shuttle glow is dependent upon the angle-of-attack for the exposed surface material. When the thermal distribution of the atmospheric gases is combined with the bulk flow of the gas relative to shuttle, this attitude dependence is almost fully explained by the incoming particle flux (Swenson et al., 1986a). These authors have further speculated that the presence of glow on surfaces having large ram angles is due to a reflected atmospheric component - the validity of which seems at odds with Slanger (1986) who contends that it is only the primary flux which contributes substantially to the glow. The altitude dependence in the shuttle glow intensity has been qualitatively found to scale with altitude according to the atmospheric atomic oxygen concentration (Mende et al., 1984a) although the circular orbits normally used for shuttle missions do not easily lend themselves to such rigid analysis. However, it is of interest to note that just such a variation has been found for satellite glow measurements (Yee et al. Abreu 1983). Peak emissions (at 6800 A and 250 km) for the shuttle glow are on the order of 500 R/A for the edge-on viewing geometry (Swenson et al., 1986a). When normalized to an outward looking profile the intensity is 12 R/A - approximately 20 times more intense than satellite data obtained under similar conditions.

Recently, Kendall et al. (1986) have reported that extremely weak shuttle glow intensities were observed on Mission STS 41-G under quite favorable conditions; that is, optimum altitude, attitude and viewing geometry. Subsequently, Swenson et al. (1986b) have found that the temperature of the exposed shuttle surface affects the glow intensity and that the AE satellite data, originally at odds with the absolute shuttle measurements, is consistent. A more detailed description of this process follows.

In an early qualitative analysis of the shuttle glow, Banks et al. (1983) found that the intensity e-fold fall-off distance from the surface was between 5 cm to 10 cm. A more detailed analysis has shown that this radiative decay length is closer to 20 cm (Yee and Dalgarno, 1983) although their appears to be a secondary contribution having an e-fold distance of about 1 m (Slanger, 1983; Swenson et al., 1986a). The tacit assumption is that the spatial extent of the glow is determined by the lifetimes of excited molecular species which leave the spacecraft surface. Significantly, Mende et al. (1983) have reported that the e-fold distances for distinctly different surface materials are the same although the relative glow intensities vary considerably. This fact has been interpreted by Swenson et al. (1986b) as lending credence to the temperature dependence discussed above.

Measurements of the shuttle glow spectrum have been attempted by Mende et al. (1986) and by Torr and Torr (1985) using spectral resolutions of 35 A and 6 A, respectively. The former authors have found that the glow emission was spectrally diffuse with a peak intensity near 6800 A whereas the latter have identified discrete emissions from excited N_2. The differences in the spectral resolution of the instruments were not sufficient to explain the discrepancy. Mende et al. (1986) has suggested that the apparent difference is the result of a column-integration of the glow emission for the outward-looking instrument used by Torr and Torr versus his technique for edge-on viewing of the glow. Existing satellite data sets, on the other hand, have very limited spectral information making it uncertain whether the unexplained emission is spectrally discrete, diffuse, or a combination (Abreu et al., 1985; Prince, 1985; Langhoff et al., 1983; Slanger, 1983).

It is not clear that any single mechanism is responsible for the shuttle glow and, indeed, it is likely that several processes may be operating simultaneously to produce the observed emission. But, perhaps the most appealing, and consistent, explanation for the shuttle glow is from the catalytic recombination of atmospheric gases on shuttle surfaces leading to the formation of NO_2 as proposed by Swenson et al. (1985). Although this process was originally discussed by Torr (1983) in connection with the AE results, the spectral distribution for

A-1

emission from the NO_2 continuum was at odds with shuttle glow measurements (Mende et al. 1984a). Swenson et al. (1985) suggested, however, that the fast recombination of NO with ramming O atoms and the spectrally-varying radiative decay lifetime of NO_2 could account for the observed spectral shift. Supporting evidence for this mechanism is provided by an apparent temperature dependence in the glow intensity (Kendall et al., 1986; Swenson et al., 1986b) which was consistent with AE satellite and Dynamics Explorer (DE) satellite mass spectrometer data showing a temperature-dependence for the heterogenous recombination of NO_2 on spacecraft surfaces (Engebretson et al, 1986). Specifically, when the spacecraft surface is cold the density of nitric oxide present, available for reactions with the incoming oxygen is greater.

Secondary sources for the glows emanating from locations above shuttle surfaces might be; 1) gas-phase interactions of shuttle contaminant gases and the atmosphere (Kendall et al. 1986), 2) surface-catalyzed reactions, similar to the NO_2 process described above, leading to emissions from excited N_2, O_2 and NO (Green, 1984), 3) reactions involving atmospheric gases and surface materials (Green and Murad, 1986; Slanger, 1983). An additional explanation for the glow which involves a plasma two-stream instability has been proposed by Papadopoulos (1984) although Slanger (1986) and Kofsky (1984) have noted that certain observational characteristics of the glow make such a contribution to the glow quite minor at best.

MEASUREMENT TECHNIQUES

Mission description

Shuttle Mission 41-G was launched into a 57° inclination orbit on October 5, 1984. Two separate time periods were identified prior to launch during which sets of glow measurements would be attempted. The shuttle altitudes during these times was 360 km and 230 km on October 6 and October 9, respectively. A Orbiter attitude was chosen which would optimize glow measurements on the port side of the rear stabilizer simultaneous with having the projection of the 100 km airglow layer, as seen from the aft-flight deck, perpendicular to and halfway up the rear stabilizer. This, so-called, OGLOW attitude was defined with a nominal pitch, roll, and yaw of 0°, -90°, and 180°, respectively. For the two periods under consideration, the shuttle assumed the attitude approximately 10 minutes before the glow measurement but had maintained a-ZLV (Payload-to-earth) attitude for at least the prior hour. The data was taken on the morningside of midnight while the Orbiter was in the southern hemisphere at mid latitudes. Based on the earlier STS-9 data of Swenson et al. (1986a) it was our expectation that the glow intensity for the low and high altitude cases would be of approximately 807 R/A and 73 R/A based, respectively.

Instrument Characteristics

The instrument complement used with the APE and OGLOW was an image-intensifier optically coupled to a standard 35-mm Nikon F-3 camera using high-speed film, Kodak type 2484. The intensifier used with each was a Noctron-V second generation device having an extended red S-20 photocathode. The basic hardware configuration, without the interferometer, for the APE instrument is illustrated in Figure 1. The OGLOW hardware differed only in its use of a f/1.4 85-mm objective lens in place of the APE's f/1.2 55-mm lens. The similarities between the basic instruments and the use of standard NASA equipment for the camera and lenses provided redundancy in the event of instrument damage or failure. The interferometric techniques differed in that the APE used a filtered Fabry-Perot optical system whereas the OGLOW used a series of narrow band filters and a filter-tilting mechanism. Each technique offered a simple, but effective, tool for obtaining photometrically accurate images of the shuttle glow and atmospheric optical emissions in high spectral resolution.

The Fabry-Perot etalon used with the APE was 3 inches in diameter by 1.5 inches thick and was mounted directly forward of the 55-mm lens. The quartz optics were coated for measurements over the wavelength range of 6000 A to 8000 A although separate medium-width interference filters were used in conjunction with the etalon to limit the spectral bandpass of the instrument. The etalon was manufactured with a plate separation of 61 microns to provide a free spectral range of 40 A with a finesse of 10. The three 100-A wide filters, each of which was used separately, were centered at wavelengths of 6563 A (H), 7319 A (OII), and 7620 A (O_2). The H alpha was used for convenience - the measurement was actually intended to detect possible emissions from the N_2 1st Positive system. Although the free spectral range of the etalon was less than the bandpass of each filter, the subsequent overlapping of orders was not considered to be of serious concern in the analysis of either the spectrally diffuse shuttle glow or discrete airglow emissions.

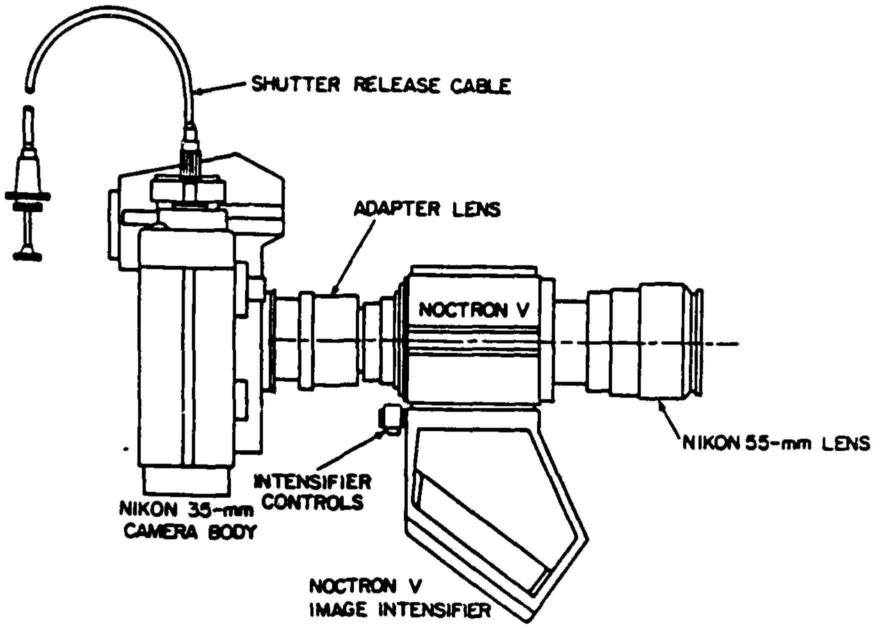

Figure 1. Hardware configuration for APE instrumentation.

The set of interference filters used with the OGLOW had center wavelengths of 5583.0 A (OI), 6307.8 A (OI), 7300.8 A (OH), 7331.8 (OII), 7642.4 A (O_2), and 7784.2 A (OI), all referenced at normal incidence. The bandpass for each filter was no greater than 4 A with a normal-angle transmittance of approximately 0.5. In a manner similar to a Fabry-Perot interferometer these narrow-band filters provide a wavelength dependent transmittance respect to the angle of incidence. This configuration utilized a spatial scanning technique which provided an effective bandwidth of 30 A across the image plane with a nominal resolution equal to the filter bandpass. The center wavelengths were slightly longer than the emissions of interest in order to provide a limited amount of spectral scanning on either side of the nominal emission feature. When the filter was tilted the nominal center wavelength was shifted to the edge of the image plane so that a total spectral bandwidth of approximately 110 A could be scanned. Therefore, the spectral resolution and bandwidth for the OGLOW instrument were quite comparable to those of the APE.

Both the APE and OGLOW instruments underwent a pre- and a post-flight calibration using a standard light source. The response for the APE image intensifier was unchanged during the mission although an increase in the fog density of the film was evident. The OGLOW instrument suffered a brief exposure to direct solar illumination which damaged portions of the intensifier and slightly reduced its overall sensitivity. A in-flight calibration of the OGLOW instrument after the accidental exposure was performed using the known intensity for certain airglow featurs. This calibration was in agreement with the post-flight tests. The characteristic curve for the APE system response is shown in Figure 2. These measurements were made using a 557.7 nm +/- 5 nm filter and no etalon. The abscissa is provided in units of Rayleigh-seconds to remove the effects of the varying exposure times (from 1/125 sec to 2 sec) and of different source intensities (from 4.1 R/A to 3.7 kR/a). Correction factors for the transmittance of the Fabry-Perot etalon and for the spectral response of the intensifier system have been included in the present analysis.

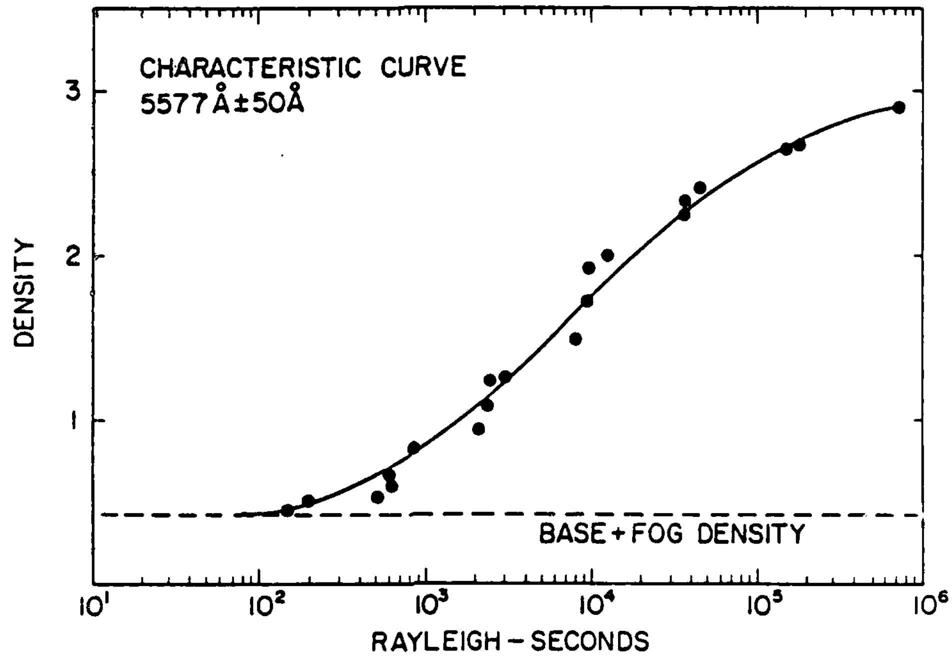

Figure 2. Characteristic curve for the APE film calibration

Auroral and Airglow Measurements

In addition to the glow measurements which were attempted during this mission were sets of auroral and airglow observations. These former measurements have been described in detail elsewhere (Denig et al., 1986; Mende et al., 1986) although they are reviewed here to demonstrate the performance of the instruments.

A series of auroral observations were made as the Orbiter traversed the southern auroral zone (peak geomagnetic latitude of 66^o) at an altitude of 236 km on October 7, 1984 near 1700 GMT. At the time of the observations, the 3-hour K_p index of magnetic activity was 4, on the recovery side of a moderately sized substorm. Figure 3a is an auroral image obtained with the APE data using a 4278 A filter sensitive to the 1^{st} negative transition of N_2^+. The Fabry Perot etalon was not used for this measurement. A limb-scan plot the absolute intensity versus altitude is shown in Figure 3b where a peak emission of 44 kR was detected along a line of sight corresponding to a limb tangent height of approximately 100 km. The e^{-1} fall-off with intensity is about 6 km. This data is directly comparable to a model of the predicted 4278 A emission resulting from the interaction of the diffuse aurora with the atmosphere. Specifically, the auroral energy deposition model of Strickland et al. (1983) was combined with the Hardy et al. (1985) statistical model of auroral energy input for this level of activity to predict the 4278 A emission rate. The average energy per electron and the energy flux estimated from the statistical model for the midnight time sector at a K_p=4 are 3.46 keV and 3.90 ergs/cm-sec, respectively. On the other hand, the energy deposition model predicts that 2.5 keV gaussian auroral electron beam of this energy flux would yield a 4278 A peak intensity of 40 kR in the limb near 108 km and with a e^{-1} fall-off of about 7 km. For a slightly higher energy beam the peak altitude would be somewhat less. This excellent agreement between the model and the data indicates that the sensitivity of the APE hardware was nominal.

An illustrative example of the use of the APE instrumentation for airglow measurements is shown in Figure 5a which an image of the O_2 atmospheric band obtained using the Fabry-Perot etalon in combination with a 7619 A +/- 50 A interference filter. The perspective of the camera to the shuttle and the earth is similar to the auroral image described above. The series of concentric rings present in the data are the rotational-vibrational band structure for the R_Q and P_Q branches of the 0-0 vibrational band (Skinner and Hays, 1985). A radial microdensitometer trace, corrected for film response, is shown superimposed on the image. This trace can be compared to the synthetic spectrum in Figure 4b for the rotational-vibration band structure at 300 °C which has been convoluted for the nominal spectral resolution and bandpass of the system (T. Slanger, private communication, 1986). Multiple orders of the two branches are present due to the width of the filter (100 A) relative to the free spectral range of the etalon (40 A). Note the spectral resolution of the instrumentation, 4 A, was sufficient to barely resolve the fine structure within each band. In other words, the spectral resolving power of the instrument was nominal.

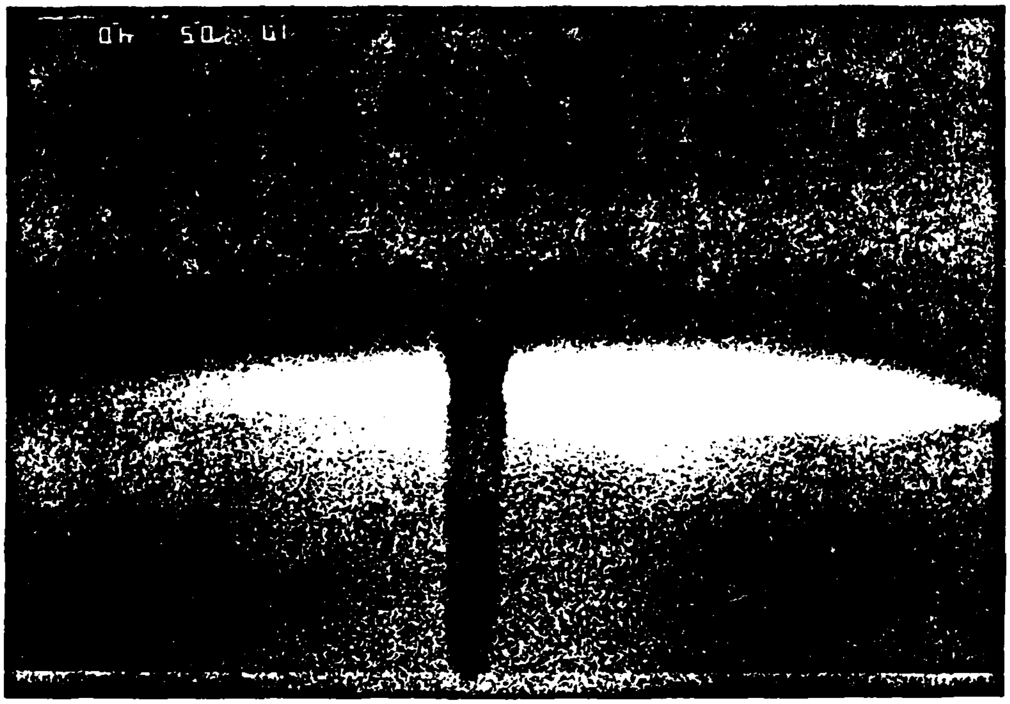

Figure 3a. Auroral image at 4278 A recorded on Mission STS 41-G

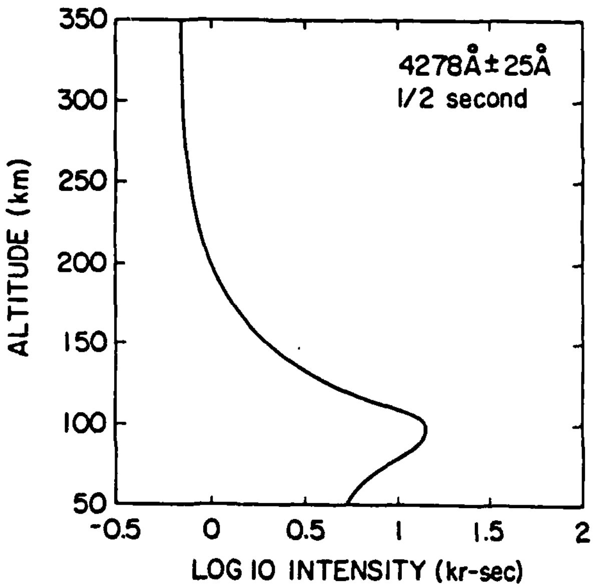

Figure 3b. Limb-scan height profile for the 4278 A emission of N_2^+.

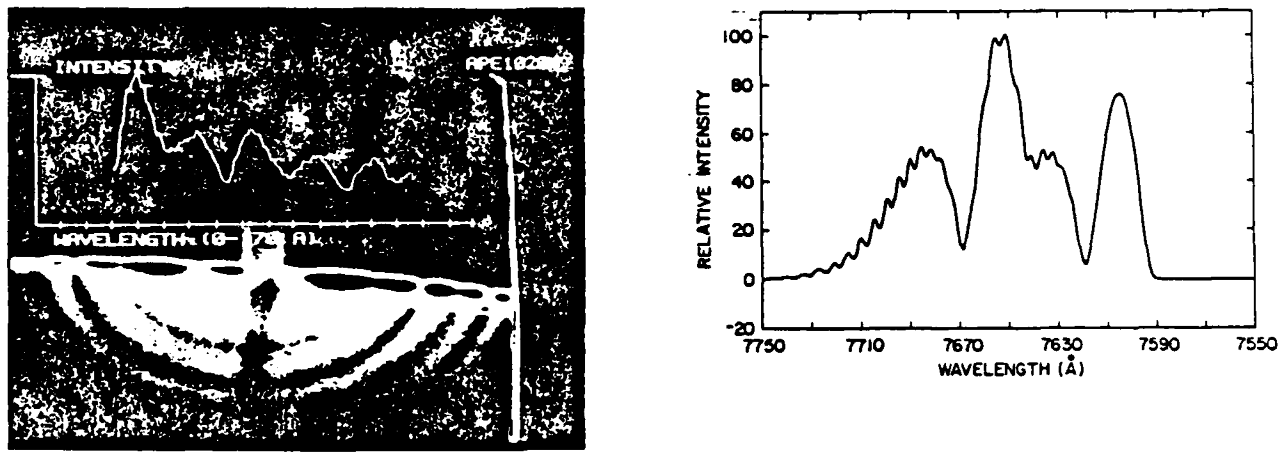

Figure 4. a) Image of the atmospheric band emission of O_2
b) Synthetic spectrum for the rotational-vibrational of O_2 convolved with the instrument spectral response.

OBSERVATIONS

Simultaneous measurements of the shuttle glow were attempted by the APE and OGLOW experiments at altitudes of 360 km and 230 km while the Orbiter was in the OGLOW attitude. The Fabry-Perot measurements of the O_2 atmospheric airglow emission at 7620 A described in the last section were part of the higher altitude glow experiment. Looking in detail at the shuttle surface of Figure 4 reveals no evidence of an off-surface glow along the port side of the stabilizer which had been predicted. Clearly seen however are the reflections of the O_2 emission and of moonlight on the exposed shuttle surface. The lack of any measurable glow at this altitude was perhaps not surprising in that the expected intensity was estimated to be more than an order of magnitude less than the radiance measured on earlier missions at lower altitudes. Indeed, the expected radiance from the glow at 7620 A was on the order of 45 R/A which was comparable to the APE instrument sensitivity for a spectrally diffuse emission within this wavelength band. Examination of all the glow data obtained at this altitude has yielded negative results although the instruments capabilities to measure the glow radiation were marginal at best.

Due to the increase in the atomic oxygen density at the lower altitudes the predicted glow intensities over all spectral bands of the APE and OGLOW were well within the capabilities of the respective instruments. An sample of the OGLOW data is shown in Figure 5a for a narrow-band 7300 A filter used in a tilted configuration. The damage to the OGLOW intensifier is clearly evident in the image and an accompanying sketch has been provided in Figure 5b to assist in the interpretation. In spite of the damage, the sensitivity of the optical system within this bandpass was approximately 140 R/A compared to an expected glow intensity of 650 R/A at 230 km. The bright airglow emission feature, the intensity of which was modulated by the spectral scanning of the narrow band filter, was from the $Q_1(1)$ line of the 8-3 band of OH at 7275 A. However, no observable glow was present in the image in Figure 5a. Similar analyses for images obtained at 5577 A, 6300A, and 70 A were also negative. A summary of result for the analysis of the OGLOW data obtained at this altitude is provided in Table 1.

The APE experiment also contributed to the set of glow measurements obtained at the lower altitude. The images presented in Figures 6 and 7 were photographed within 100 A bands centered at 6563 A and 7319 A in combination with the Fabry-Perot etalon. In spite of the increased sensitivity of this system over the OGLOW instrument, no quiescent glow could be detected. Table 1 includes a upper bound on the intensity of the glow which was limited by the instrument sensitivity of 50 R/A. As a point of comparison, the anticipated glow intensities for the 6563 A and the 7319 A bands were 740 R/A and 650 R/A, respectively.

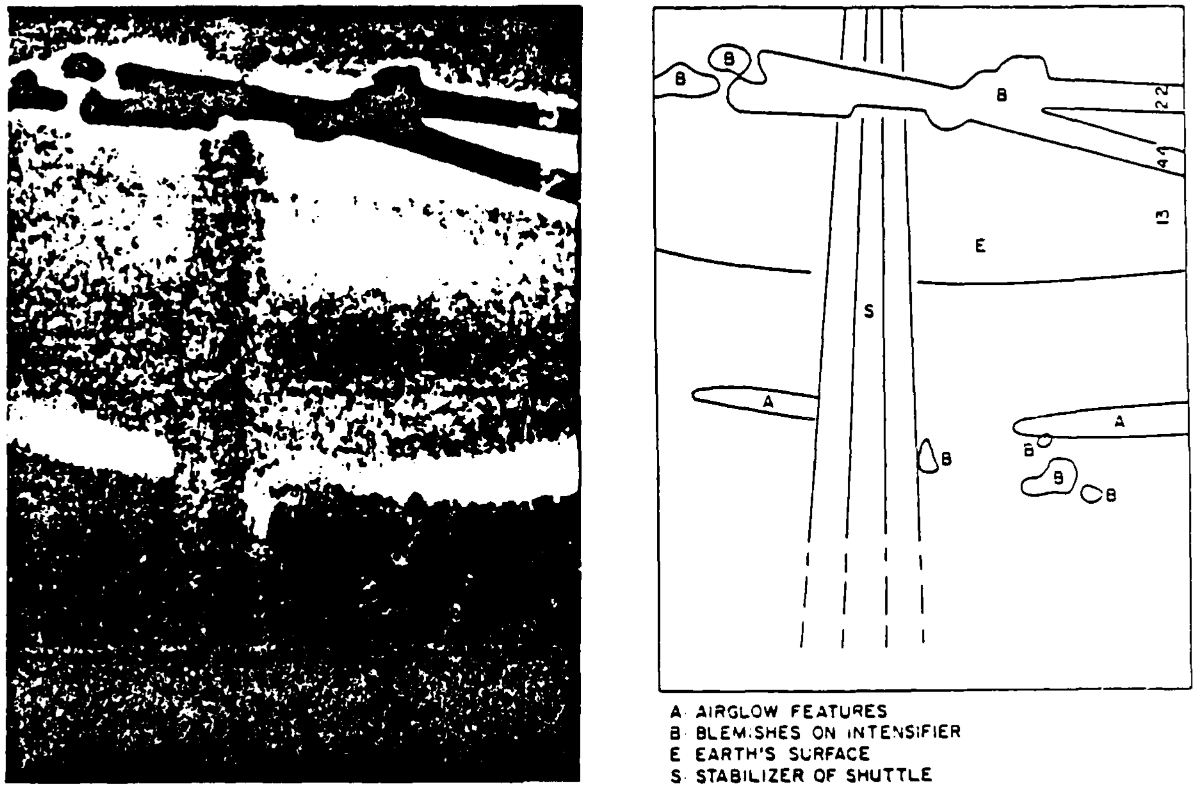

Figure 5. a) OGLOW photograph of the rear stabilizer at an altitude of 230 km taken with a narrow bandpass filter at 7300 A in a tilted configuration. Note the bright airglow layer and the absence of glow on the stabilizer.
b) Sketch identifying the main features of the OGLOW photograph.

TABLE X. Quiescent Glow Results

Wavelength	Brightness (R/A)	
(nm)	OGLOW (230 km)	APE (230 km)
5577	<50	
6300	<90	
6563		<50
7300	<140	<50
7600	<160	

The only evidence for any type of glow seen in these data sets were of the thruster-enhanced glow. Figure 8 is a photograph within 100-A bandpass around 7620 A during the combined APE-OGLOW experiments. Barely discernable within the image is a region of extended glow on the port side of the rear stabilizer which is not seen in a photograph taken some 14 seconds later using identical camera settings. The observed glow was perhaps induced by gases released by the

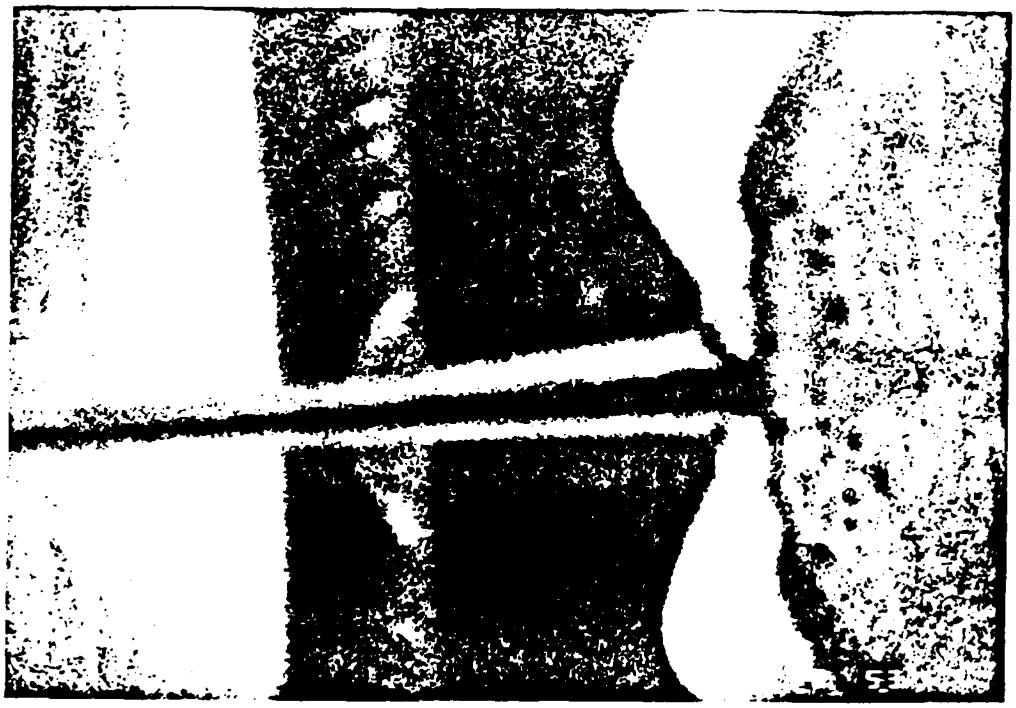

Figure 6. APE image photographed at GMT/13:37:53 with a 6563 A filter and etalon.

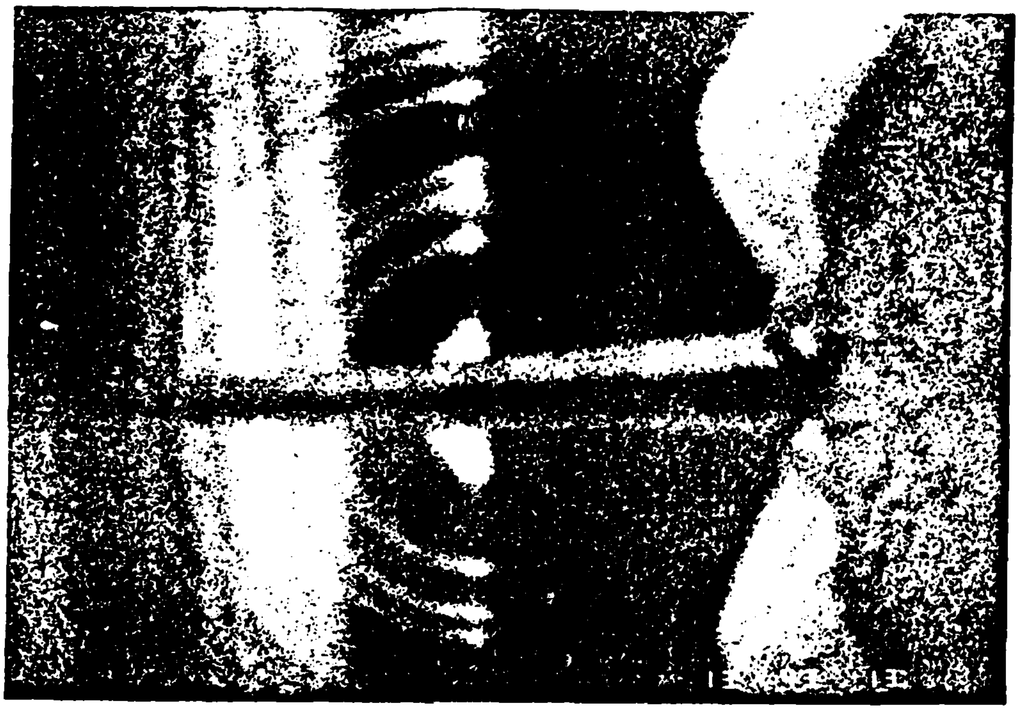

Figure 7. APE image photographed at GMT/13:43:13 with a 7319 A filter and etalon.

a ..itude control system (ACS) which operated during or just prior to time of the photograph. Due to uncertainties in the time of the gas release relative to the 8-second exposure for the photograph, an absolute determination of the glow intensity was not possible. Of interest however was the lack on any discrete spectral features in the induced glow, showing that this within this band the thruster-induced glow was a continuum at the 4-A spectral resolution of the Fabry-Perot etalon and filter system.

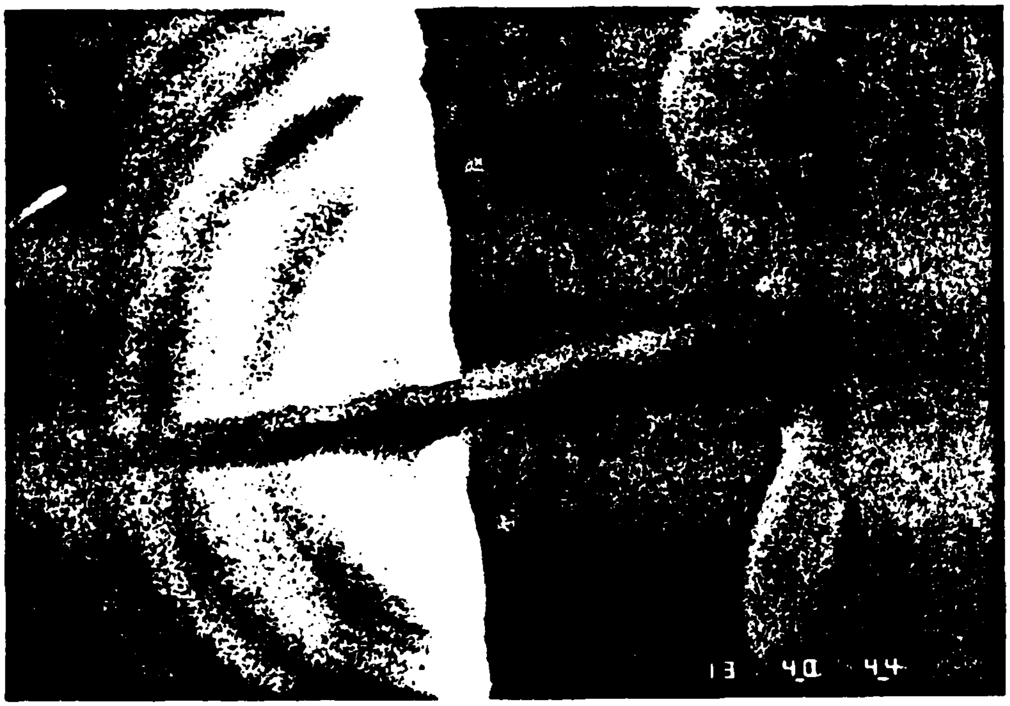

Figure 8. APE image recorded at GMT 283/13:40:44 with the 7620 A filter and etalon. Note the presence of the thruster-induced glow which is barely discernable on the port side of the rear stabilizer.

DISCUSSION

The most puzzling aspect of the APE and OGLOW measurements was the apparent of lack of quiescent glow seen in the data limited by the sensitivity of the instrument and interference from contaminant light sources. At the time of these measurements our experience (Mende et al., 1984) lead us to believe that for an altitude of 230 km the glow intensity as seen from the perspective of the aft flight deck should have been roughly 380 R/A at the peak emission and 350 R/A, 310 R/A, and 240 R/A at the respective wavelengths of 6563 A, 7319 A, and 7620 A. The detailed analysis of the STS-9 data (Swenson et al. 1986) predicted even higher glow levels of 740 R/A, 650 R/A, and 500 R/A, respectively within these three wavelength bands.

Swenson et al. (1986b) have interpreted these results as lending credence to their theory of the glow which is based on the NO_2 continuum emission. The justification, which are better described the referenced paper, is that the surface temperature of the rear stabilizer during the glow observations was responsible for the extremely low emission levels. Specifically, due to the extended period during which the shuttle was in the -ZLV (payload bay to earth) attitude the surface temperature of the stabilizer was greater than that estimated for earlier missions. That is, the topside of the shuttle was kept relatively warm prior to these measurements since the surface radiated towards the earth whereas on earlier missions, notably STS-9, the surface was allowed to radiate into deep space and maintained a colder temperature. Since the NO_2 theory of Swenson et al.'s (1985) requires the availability of surface NO for reactions with incoming atmospheric O, the high surface temperatures and the apparent lack of glow emission implies that the surface density of NO was small. Supporting evidence has been provided by the DE mass spectrometer data of Engebretson and Hedin (1986) which indicates that the availability of NO on spacecraft surfaces is enhanced on colder surfaces. Presumably, the NO is formed by surface reactions involving atmospheric gases. Thus, the present data would appear to support the contention of Swenson et al. (1986b).

CONCLUSIONS

A series of shuttle glow measurements made by both the APE and OGLOW experiments at altitudes of 360 km and 230 km aboard the Challenger in October 1984 have revealed no evidence for emission under quiescent (no thruster operation) conditions. These data have been used to support the theory of Swenson et al. (1986b) which contends that the radiant emission from the NO_2-continuum is the primary source of the near-surface shuttle glow. The thruster-enhanced glow, which arguably may be due to a source other than NO_2 mechanism, is spectrally continuous within the 4 A resolution of the optical systems.

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